

# Diminished equilibrium magnetization in Hg-1223 and Tl-2212 superconductors with fission-generated columnar defects

J.R.Thompson <sup>a, c, 1</sup>, J.G. Ossandon <sup>b</sup>, D.K. Christen <sup>a</sup>, K.J. Song <sup>c</sup>, H.J. Kim <sup>c</sup>,  
L. Krusin-Elbaum <sup>d</sup>, K.D. Sorge <sup>c</sup>, J.L. Ullmann <sup>e</sup>

<sup>a</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6061 USA

<sup>b</sup>Dept of Engineering Sciences, University of Talca, Curico, Chile

<sup>c</sup>Dept of Physics, University of Tennessee, Knoxville, Tennessee 37996-1200 USA

<sup>d</sup>IBM Research Center, Yorktown Heights, 10598 NY

<sup>e</sup>Los Alamos National Laboratory, Los Alamos, NM 87545 USA

---

## Abstract

When randomly oriented columnar defects (CDs) are added to Hg-1223 and Tl-2212 superconductors, their vortex state equilibrium magnetization  $M_{eq}$  decreases substantially.  $M_{eq}$  progressively deviates from the usual London  $\ln(B)$  dependence and the curves become  $S$ -shaped. Vortex-defect interactions quantitatively account for this behavior.

*Key words:* equilibrium magnetization; columnar defects; Tl-cuprates; Hg-cuprates;

---

## 1. Introduction

The usage of columnar defects (CDs) to enhance the current-carrying capacity of high- $T_c$  superconductors has been widely explored and shown to be quite effective in increasing the pinning of vortices. This increased current density is evident, for example, in the irreversible magnetization. Less well explored, however, are the accompanying effects on the *equilibrium* magnetization  $M_{eq}$  of the superconductor, which are non-trivial. [1,2] In this work, we study and analyze changes in  $M_{eq}$  in Hg-1223 and Tl-2212 cuprate superconductors brought about by doping with randomly oriented CDs, created by a fission process. [3]

Samples for study were bulk polycrystalline  $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_x$  (Hg-1223) and  $\text{Tl}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}_x$  (Tl-2212) materials containing sets of 3 and 2 adjacent oxygen-copper layers, respectively. The samples

were irradiated in air at room temperature at the Los Alamos National Laboratory with 0.8 GeV protons. The process creates CDs by inducing fission of heavy Hg or Tl nuclei, whose fission fragments form randomly oriented latent tracks. Proton fluences  $\Phi_p$  in the range  $0.35 \times 10^{16}$  protons- $\text{cm}^{-2}$  were used to form defects whose areal density corresponds to a “matching field”  $B_\Phi$  of 0-3.4 T. The superconductive properties were investigated magnetically using a SQUID-based magnetometer (Quantum Design MPMS-7). We obtained  $M_{eq}(H, T)$  by averaging  $M$  measured in increasing- and decreasing-field history (to allow for slight irreversibility) and correcting for background signals measured above  $T_c$ .

## 2. Experimental results

For the as-prepared materials, the equilibrium magnetization follows a simple London dependence with  $M_{eq}(H, T) \propto (1/\lambda^2) \ln(\beta H_{c2}/H)$ . This is illustrated in Fig. 1, a semilogarithmic plot of  $M_{eq}(H)$  for the mate-

---

<sup>1</sup> Corresponding author: Oak Ridge National Lab, P.O. Box 2008, Oak Ridge, Tennessee 37831-6061 USA E-mail: JRT@UTK.EDU

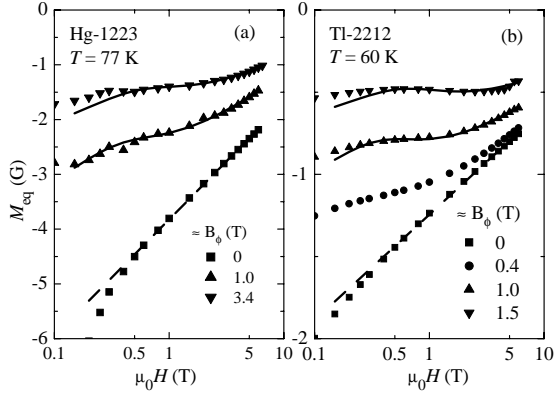


Fig. 1. The equilibrium magnetization  $M_{eq}$  versus magnetic field (logarithmic scale) for Hg-1223 and Tl-2212 superconductors at  $T = 77$  and  $60$  K, respectively. For the as-prepared materials,  $M_{eq}$  follows a simple London  $\ln(H)$  dependence; adding randomly oriented columnar defects steadily decreased the magnitude of  $M_{eq}$  and changed its field dependence. Solid lines show fits to Wahl-Buzdin theory Eq. 1; see text.

rials at  $T = 77$  and  $60$  K, which corresponds to  $T/T_c \approx 0.6$  for the respective cases. The straight dashed lines are fits to the London expression, yielding values for the London penetration depth  $\lambda(T)$  that are well behaved and comparable with results of other studies.

The behavior changes progressively when randomly oriented CDs are added. As is very evident in Fig. 1, the magnitude of  $M_{eq}$  steadily decreases with increasing defect density  $B_\Phi$ . In addition, the field dependence becomes “S”-shaped. These features are consequences of changed energetics in the vortex system: in addition to the usual vortex-vortex repulsion responsible for the simple London dependence, CDs introduce an attractive vortex-defect interaction. The latter is field dependent, since an underfilled defect landscape with  $B < B_\Phi$  can pin most vortices, while an overfilled array with  $B > B_\Phi$  leaves an increasing number of vortices unpinned. Assuming randomly located CDs, Wahl-Buzdin [1] derived the following:

$$M_{eq} = -(\varepsilon_0/2\Phi_0) \times \ln(\beta H_{c2}/B) - (U_0/\Phi_0) \left\{ 1 - \left[ 1 + \frac{U_0 B_\Phi}{\varepsilon_0 B} \right] \exp\left(-\frac{U_0 B_\Phi}{\varepsilon_0 B}\right) \right\} \quad (1)$$

where  $\varepsilon_0 = [\Phi_0/4\pi\lambda_{ab}]^2$  is the line energy,  $U_0$  is the pinning energy, and  $B = (H + 4\pi M) = H$  since  $M$  is small. The first term is the usual London contribution and the second reduces the magnitude on  $M_{eq}$  due to interactions with defects. While this expression was derived for the case of a magnetic field aligned with parallel CDs, it can be applied [4] in cases when high superconductive anisotropy  $\gamma \gg 1$  refocuses the arrays of vortices and CDs toward the  $c$ -axis.

This expression describes the experimental results reasonably well. In Fig. 1, the continuous curves show Eq. 1 fitted to these data. For each material, we find the reasonable result that, for data at a variety of temperatures, the pinning energy  $U_0 \approx (0.65 - 0.9) \times \varepsilon_0$  for Hg-1223 and  $U_0 \approx (0.9 - 1.2) \times \varepsilon_0$  for Tl-2212. Irradiation increases values for  $\lambda$  considerably. Theoretically [1], one has  $\lambda^{-2}(B_\Phi) = \lambda^{-2}(B_\Phi = 0) \times [1 - 2\pi R^2 B_\Phi/\Phi_0]$  where  $R$  is the radius of a columnar track. For the Tl-2212 materials, [4] this expression yields  $R \approx 11$  nm using the values  $B_\Phi$  calculated from the proton fluence. For the Hg-1223 materials, we obtain  $R \approx 8.4$  nm, based on  $B_\Phi$  values taken both from the proton fluence and the fitting procedure (which effectively accounts for some overlap of CDs; details will be presented elsewhere). These values for  $R$  are larger than the transverse size of latent tracks visible in TEM. This is a consequence of both the oblique passage of ion fragments through the CuO planes and the presence of a more extended damaged region around a CD. [5]

In summary, the addition of fission-generated, randomly oriented columnar defects to Hg-1223 and Tl-2212 superconductors substantially reduces the magnitude of the equilibrium magnetization  $M_{eq}(H, T)$ . The resulting nontrivial field dependence is described reasonably well by the theory of Wahl-Buzdin.

## Acknowledgements

We thank M. Paranthaman for providing the as-prepared superconductors. Work of JGO was supported by Chilean FONDECYT grant # 1000394. Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the U.S. Department of Energy under contract DE-AC05-00OR22725. Los Alamos National Laboratory is funded by the US Department of Energy under contract W-7405-ENG-36.

## References

- [1] A. Wahl, V. Hardy, J. Provost, Ch. Simon, A. Buzdin, *Physica C* **250** (1995) 163.
- [2] C. J. van der Beek, M. Konczykowski, R. J. Drost, P. H. Kes, N. Chikumoto, S. Bouffard, *Phys. Rev. B* **61** (2000) 4259 and references therein.
- [3] L. Krusin-Elbaum, J. R. Thompson, R. Wheeler, A. D. Marwick, C. Li, S. Patel, D. T. Shaw, P. Lisowski, J. Ullmann, *Appl. Phys. Lett.* **64** (1994) 3331.
- [4] J. G. Ossandon, J. R. Thompson, L. Krusin-Elbaum, H. J. Kim, D. K. Christen, K. J. Song, J. L. Ullmann, *Supercond. Sci. Technol.* **14** (2001) 666.
- [5] Yimei Zhu, Z. X. Cai, R. C. Budhani, M. Suenaga, D. O. Welch, *Phys. Rev. B* **48** (1993) 6436.